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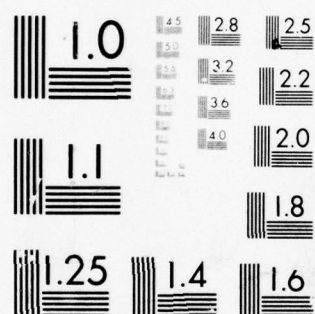   JAN 78   R SIMON, D V TURNQUIST   DAAB07-76-C-1301
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Research and Development Technical Report

ECOM -76-1301-5

REPETITIVE SERIES INTERRUPTER II

Robert Simon
David V. Turnquist
EG&G Inc.
√ Electronic Components Division
Salem, Massachusetts 01970

January 1978

Fifth Triannual Report for the Period 1 June 1977 to 30 September 1977

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Prepared for:

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Further development of the Repetitive Series Interrupter thyratrons is described. A series of tubes containing magnetic interaction regions with chuted wall internal surfaces has been designed and is under construction. Efforts to eliminate restrike continue with the study of grid biasing and anode-grid region magnetic field pulsing. Alternate interruption geometries are tested.

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ABBREVIATIONS AND SYMBOLS

Bq	Magnetic field (kilogauss) required for reducing fault current to zero
Ebb	Main supply voltage for tube under test
Ef	TUT cathode heater filament voltage
egk	Instantaneous forward grid voltage
ξj	Magnetic field energy for RSI tube volume
EM	Magnet supply voltage
epy	Instantaneous full voltage across tube under test
Eres	TUT hydrogen reservoir voltage
Eq	Magnet circuit voltage required for quenching fault current
etd	TUT voltage drop during normal pulse operation
Ib	Average forward anode current
ib	Peak RSI-carried current
iRSI	RSI-carried current, as a function of time
L	Length of interaction tube used during test
m	Empirical exponent of proportionality between Bq and 1/L
MCCD	Magnetic-Controlled Charging Diode
N	Number of turns in magnet coil
P	TUT pressure
prr	TUT pulse repetition rate
r	Radius of interaction tube
Rcct	Resistance of magnetic field probe circuit
Rchoke	Resistance of magnetic field probe circuit integrating inductor
Rm	Magnet circuit load resistance
R1	Pulse-forming network load resistance
Rrc	Fault network load resistance
τD	Time delay between TUT fire and magnet fire
τr	Magnetic field risetime
TUT	Tube under test
β	Empirical exponent of proportionality between Bq and Ebb
δ	Empirical exponent of proportionality between Bq and ib
Δtad	Full range of deviation of delay time drift for tube fire

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1. INTRODUCTION

1.1 FOREWORD

This report constitutes the Fifth Triannual Report under USA ECOM Contract DAAB07-76-C-1301, entitled "Repetitive Series Interrupter II." The investigations herein described were performed from 1 June 1977 to 30 September 1977 by EG&G, Inc., 35 Congress Street, Salem, Massachusetts.

1.2 BACKGROUND

The transverse application of high (10 KG) magnetic fields to the positive column of a glow discharge has proven to be a practical method of interrupting high voltage (15 kV, 300 amp) DC current. The direction of the present study is toward inclusion of this switching phenomenon into a hydrogen thyratron-type opening switch.

Previous work led to the empirical formula $Bq = L^{-0.75} Ebb^{1.25} ib^{0.25}$ (KG, cm, kV, amps) for the magnetic field level required to interrupt a discharge in a straight discharge channel. Efforts to reduce the magnetic field energy, required for current interruption, led to studies of interruption in chuted-wall discharge channels and also in low pressure tube operation. Problems encountered included fault discharge restriking after interruption, high tube voltage drop, and, frequently, high tube jitter.

1.3 PRESENT RESULTS

Work during this period was directed toward (1) the design and construction of the RSI 10 series tubes (ceramic chute tubes), (2) the attempted elimination of restrike occurrence after fault interruption, (3) a short investigation of the effects of using grid-quenching as a fault-interrupting mechanism, (4) the design of several alternate interruption channel geometries, and (5) some experimental modifications including the installation of a 75 kV Machlett triode to simulate the characteristics of a TWT.

The RSI 10 series of six demonstration tubes (Figures 1, 2, and 3) was designed to accomplish interruption by the interaction of the magnetically driven plasma column against a chuted-wall surface. The design was based on the success of the washer-chuted RSI 005 in reducing Bq, the interrupting magnetic field level. Various interaction channel dimensions were chosen to provide a study of the relative effectiveness of differing longitudinal and transverse chute dimensions. These tubes are near completion.

Reliable restrike elimination has not yet been achieved. Three modes of restrike prevention were studied with inconclusive results: grid biasing in the -2 to -50 volt range, anode-grid magnetic field application, and interaction region geometry modification were tested without consistent success.

An S-shaped interaction channel (RSI 7-2, Figure 4), providing dielectric obstruction to the restrike discharge was constructed and tested. It was not successful in eliminating or reducing restrike occurrence.

Grid biasing of the RSI 7-2 (Figure 4) reduced restriking to as low as 0 to 5%, but not repeatedly. Best results were observed at low pressure, low Ebb, and low magnetic field level. Restriking could be partly attributed to grid noise, but other effects of egk voltage chopping and of failure of egk to reduce to ground potential during or after interruption could not. To date, changes in external circuitry have not proven capable of eliminating these effects.

An auxiliary magnetic field placed across the anode-grid gap also achieved inconsistent restrike elimination. Periods of restrike elimination at pressures as high as 0.4 torr were observed, but were mixed with more frequent periods of 10 to 50% restrike activity at equal or lower pressure.

Grid-quenching tubes were not successful. Quenching was not observed at the expected grid current density; furthermore, tube voltage drop in a thin channel narrow aperture design increased above 2 kV. Testing of high magnetic fields placed across the anode-grid gap showed little fault interruption capability in such a design.

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HY-6 ANODE CUP
HY-26 GRID CUP
HY-6 OUTER HEAT SHIELD
HY-6 BACKING RING
0.125" HY-6 BACKING RING
ANODE FLANGE TYPE #60
(DWG. A-307653, REV. C)
0.020" Cu STRESS WASHER

T. I. G. WELD

DH 146 BACKING PLATE

0.125 x 0.510 x 0.300 I.D.
BACKING RING
(ALBEROX A-16197)

0.100"

0.150"

0.300"

6.600"

0.100"

0.020" Cu STRESS
WASHER

CATHODE FLANGE
CENTER PLATE

CATHODE FLANGE
PLATE

T. I. G. WELD

7322 BACKING RING

7322 BODY CERAMIC

7322 CATHODE-RESERVOIR
ASSEMBLY

T. I. G. WELD

1 INCH

Figure 1. RSI 10A (15 kV Rating).

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HY-6 OUTER
HEAT SHIELD

HY-6 ANODE
CUP

HY-26 GRID CUP

1 INCH

7322 CATHODE-
RESERVOIR ASSEMBLY
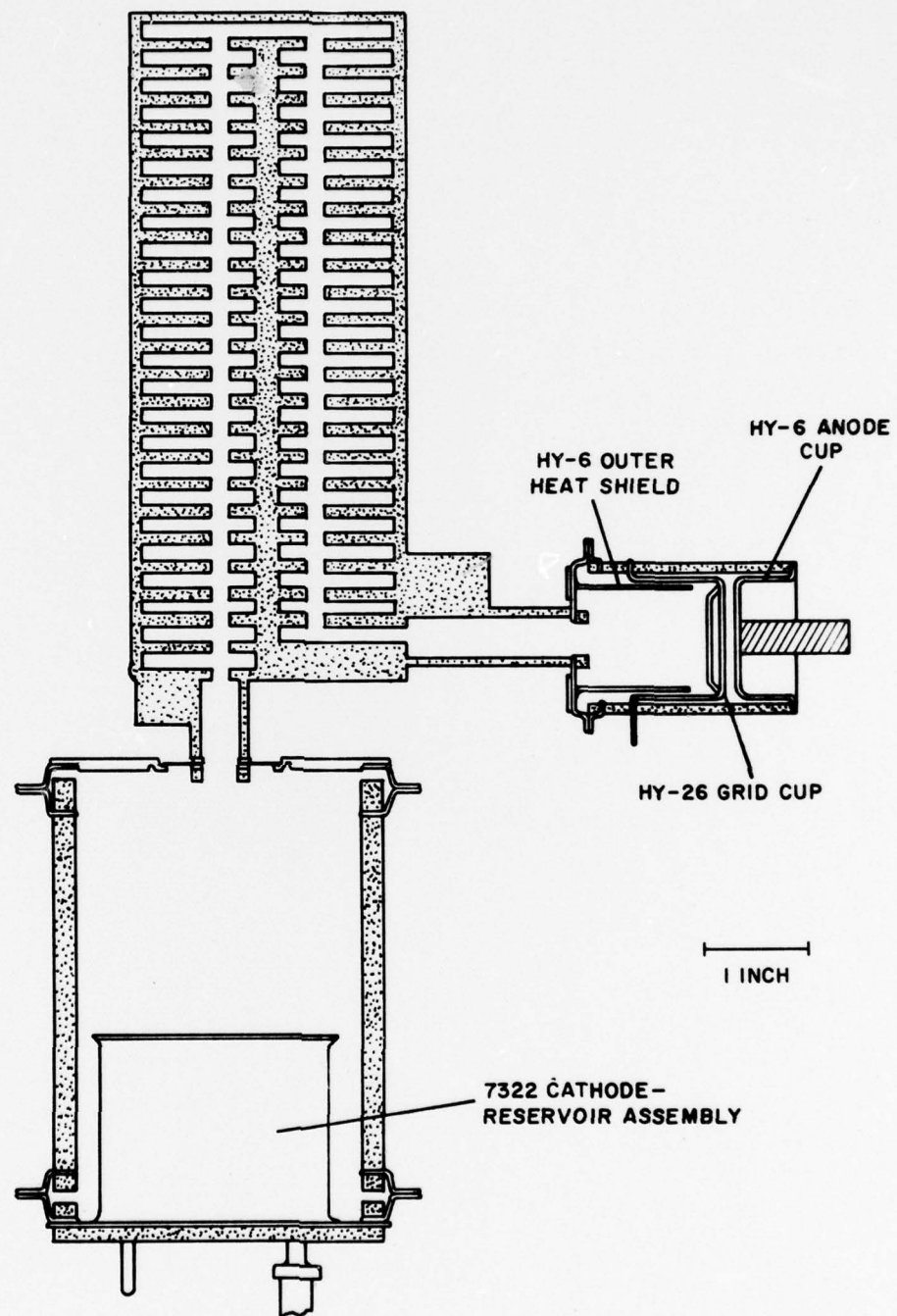
Figure 2.   RSI 10DD (30 kV Rating).

Figure 3. RSI 10 Interaction Channels.

HY-6 ANODE CUP

HY-26 GRID CUP

T. I. G. WELD

HY-6 OUTER HEAT SHIELD

T. I. G. WELD

7.5" PYREX
(7mm x 9mm)

COPPER VACUUM SEAL
GASKET, MODIFIED

TO DEMOUNTABLE
CATHODE ASSEMBLY

T. I. G. WELD
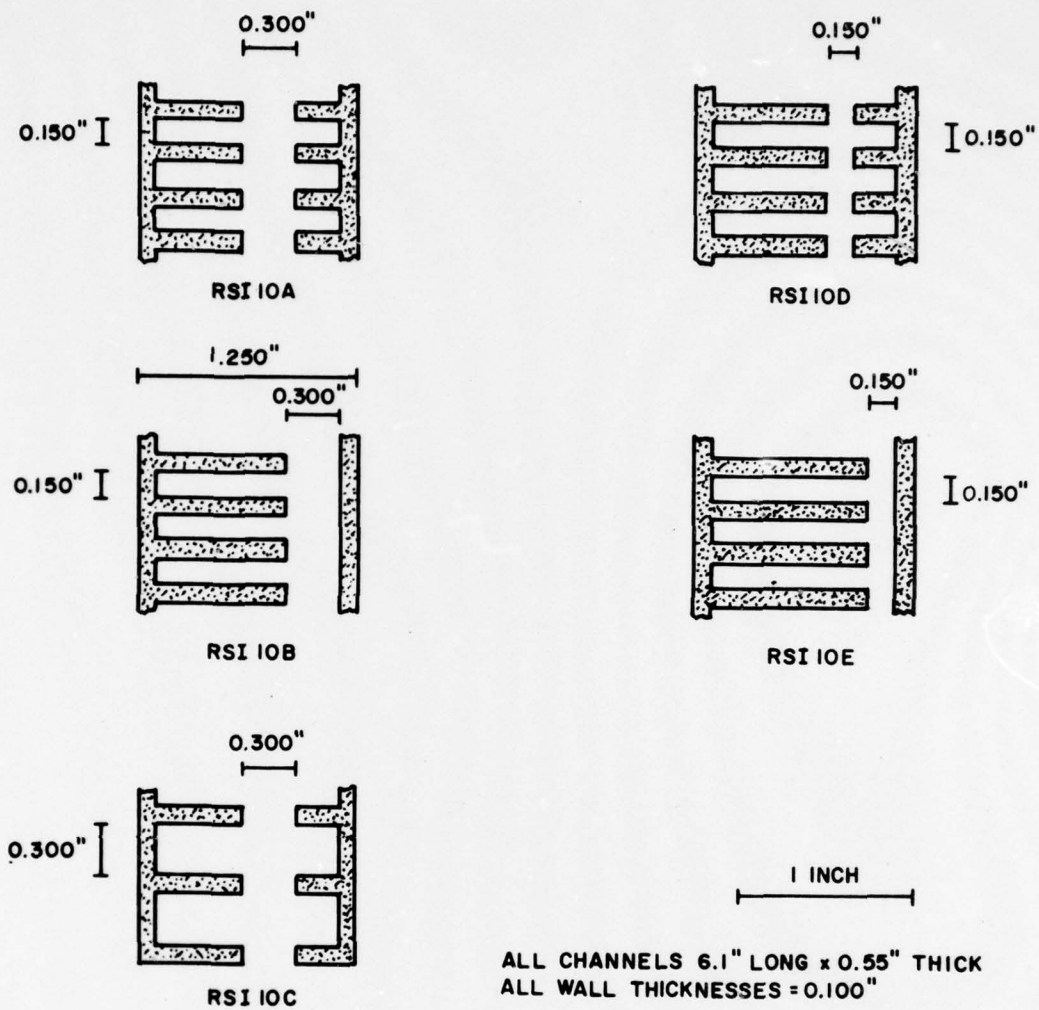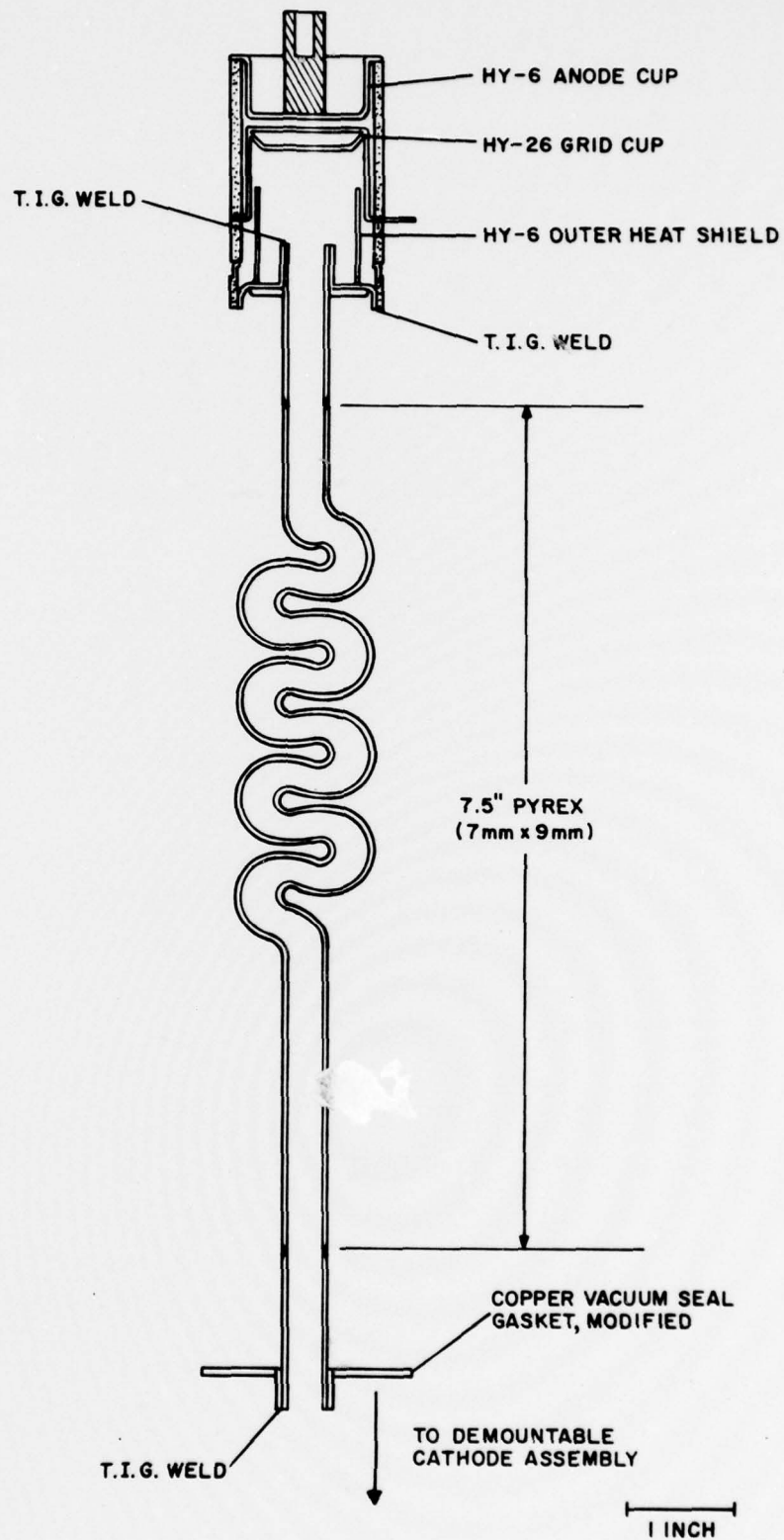
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Figure 4. RSI 7-2.

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2. PROGRESS

2.1 RSI 10 DESIGN

A chuted-wall interaction channel design was selected for the first phase demonstration tube series. Designs for the 15 kV and the 30 kV tubes are shown in Figures 1 and 2, respectively.

A modified 7322 cathode assembly (Ib capability = 2.2 A DC, ib = 1500 A) and modified HY-6 high voltage holdoff structure (epy = 16 kV) were used to meet the technical requirements of Ib = 0.8 A DC, i fault = 300 A, and Ebb = 15 kV. A six-inch high alumina-chuted ceramic interaction section was chosen to meet the requirements for etd (350 volts) and the switching magnetic field energy, ξj (50 joules). An etd of 310 volts (210-volt channel drop, 100-volt anode-grid and cathode drop), and an ξj of 25 joules are predicted for the RSI 10 series from an extrapolation of RSI 005 performance.

A variety of interaction channel cross-sections was devised for the six-tube requirement; Figure 3 shows sample cross-sections for the five 15 kV tubes. The series utilizes eight differing chute wall geometries for inter-ruption, as well as two flat interaction walls as an experimental control. Wall interaction is switched from one wall surface to the other by reversal of the magnetic field direction (resulting in a reversed $\vec{I} \times \vec{B}$ force). The 30 kV interrupter utilizes a twin, series-connected discharge column. An awkward hold-off structure location is tolerated in order to allow for maximum use of the magnetic field energy while retaining moderate simplicity of ceramic construction, and to serve as a model for future multiple-channel, chuted-wall, higher voltage interrupters.

Ceramic interaction sections for the RSI tubes are constructed from two matching halves, where the joining seams are located along the centerline of the main discharge channel. The two halves are cemented with a suitable high

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temperature glaze material. To provide some safety for leak prevention at these seal junctions, lateral wall thicknesses were increased to 0.125 inch minimum, and the central circular bore was given an increased (extended) flat wall length at the seal region.

The various dimensions chosen for the interaction sections provide a means of exploring most efficient interruption geometries. In this regard, the RSI 10A, 10C, and 10D present an immediate test of the effect of differing chute depths in interruption; RSI 10B and 10E compare chuted to unchuted surfaces. Comparisons of Bq levels among different tubes are not as accurate as comparisons within individual tubes, due to possible pressure differences, levels of gas contamination, etc. The complete RSI 10 series will provide two 4-point studies of Bq versus plasma chute depth (RSI 10A, 10B: chute depth = 0, 0.25, 0.50, 0.75 inch with a central channel of 0.300 inch diameter; RSI 10D, 10E: chute depth = 0, 0.25, 0.65, 0.90 inch with a central channel of 0.150 inch diameter). A comparison between these groups will test the importance of interruption in the central channel dimension.

2.2 RESTRIKE PREVENTION

Previous efforts to eliminate restrike behavior were directed toward the use of a weak magnetic field trailing pulse following directly on the main magnetic field interrupting pulse (Fourth Triannual report). This work was based on previous observations which showed that restrikes generally occurred: (1) when an oscillating interrupting magnetizing current passed through zero, or (2) when an RC-decaying magnet current reduced itself to some low fraction of its maximum value, that fraction being generally 10 to 50%. Results from these extended field tests revealed delayed restriking after abnormally long periods of up to 400 μsec. The cause of this behavior is unclear, but may be due to hot wall electron or gas (H_2 or possibly O_2) emission, grid hot spots, grid noise, or some as yet unknown mechanism whereby the grid-anode region fails to develop voltage holdoff capability.

Present efforts were directed toward other methods of solving the restrike difficulty. Three approaches were taken: (1) use of grid bias circuitry, (2) addition of an auxiliary magnetic field applied to the anode-

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grid section of the RSI, and (3) construction of an S-shaped interaction channel to explore effects of dielectric obstruction on restrike phenomena. The latter channel was embodied in the RSI 7-2 (Figure 4). Experiments showed an improvement in restrike reduction in the former two cases, although neither could be reproduced reliably or consistently.

Use was made of the simple grid bias circuit shown in Figure 5. Due to the high voltage developed across the interaction section during interruption, the grid is not biased relative to the cathode, but rather to an alternate point below grid potential but above the high interaction section potential. Use was made of the upper Kovar glass sealing sleeve assembly to provide a low reference point for grid biasing. Values of Lb = 2.5 mh, and C = 1 mFd provided best results for restrike elimination without loading down the required 3 kV trigger pulse. (Use of a lower impedance, high voltage trigger system might allow the use of lower Lb, and perhaps reduce grid bias requirements.)

Results from these tests were mixed; test runs provided the data shown in Figures 6 and 7, where restrike occurrence was noted to be a function of tube pressure and grid bias. Deviation from these results was seen, however, particularly if the grid bias circuitry was changed. Elimination of the grid bias voltage without elimination of the series L, C, for instance, reduced critical restrike pressure to 0.25 torr. At other times, restriking was eliminated at a particular test condition, only to reappear shortly. Tests indicated that it is more likely for a restrike to occur following an initial restrike than following a completely interrupted discharge.

An auxiliary magnet with a two-inch gap was used to provide a weak transverse field across the anode-grid holdoff structure, and was connected in series with the principal magnet coil winding. A field of approximately 300 gauss is obtained at the center of the gap.

Varied results were obtained, including the complete but unreproducible elimination of restrikes up to 0.43 torr at Ebb = 7.5 kV. Generally, restriking was reduced in frequency from 5 to 50%, with restriking occurring least frequently at low pressure, low Ebb, and low β, independently. Increasing P, Ebb, or β independently of the other two variables causes a sudden increase in restriking.
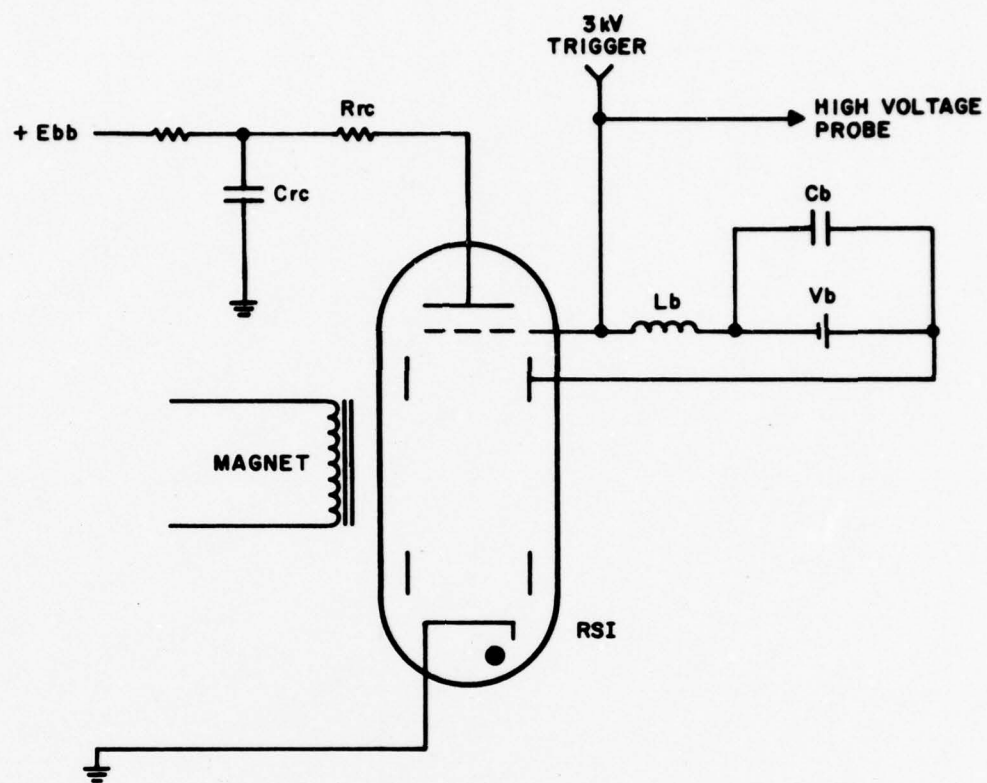
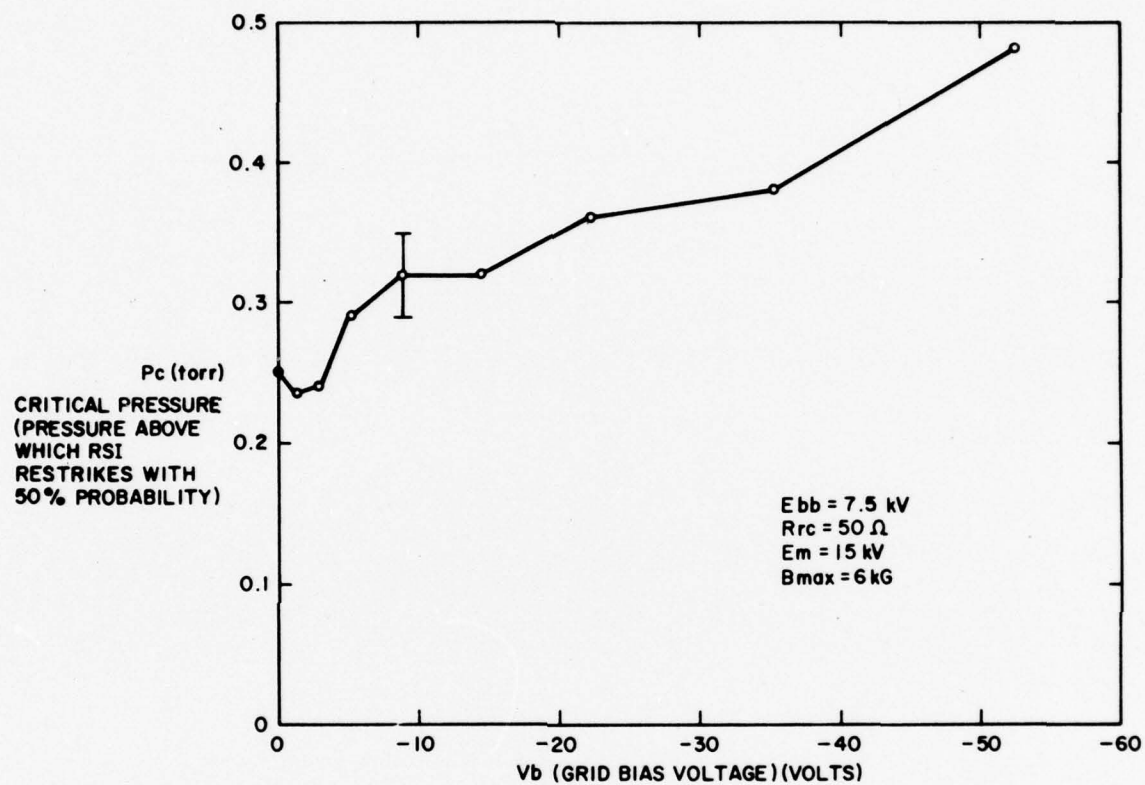Figure 5. RSI 7-2 Grid Bias Circuitry.

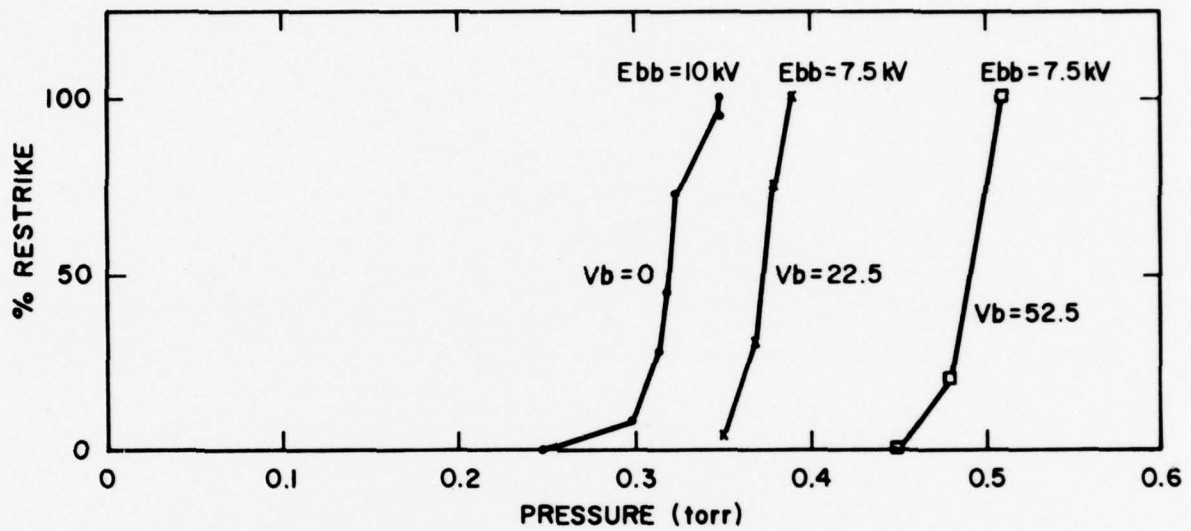Figure 6. Restrike Pressure versus Grid Bias for RSI 72.

Figure 7.   Percentage of Restrike of Fault Pulses versus
Pressure Grid Bias for RSI 7-2.

Use of the RSI 7-2 interaction channel geometry (Figure 4) did little to improve either fault interruption or restrike prevention. The tube fractured before a test was made of electric field grading (and local reversed field grading) and its effect upon restrike behavior.

The overall conclusion taken from these tests is that several mechanisms are responsible for the production of restrike activity. The first is related to grid noise, the second to a failure of high voltage transfer from the interaction region to the holdoff region, and a third to spurious causes, perhaps due to unseen grid noise.

Grid noise does appear in the present experimental arrangement, and if present at a level above approximately 1 kV will restrike the tube. One mode of restrike represents a drop of egk to a 1 to 2 kV decaying oscillation above ground. Restriking occurs as the oscillation swings upward, and may repeat itself, up to 10 or more times every 2 to 3 μsec, in a voltage chopping pattern. This chopping occurs while a high magnetic field is still present across the interaction region, so that a full restrike does not occur (i.e., epy stays at its interrupted potential). However, if chopping continues until the magnetic field is considerably reduced, as it often does, a full restrike occurs.

Grid noise caused by the magnetic field circuit also causes restriking after a period of 20 to 60 μsec, or more. This noise has been eliminated only by means of a low impedance circuit from grid to cathode ground, which also loads down the trigger pulse and prevents tube firing. This noise may be due to dB/dt induced voltages or to magnet circuit spark gap noise. Magnetic shielding of the grid-anode region was attempted, but little success in restrike elimination was observed.

Alternately, the grid potential can rise to epy after interruption but fail to fall to ground (i.e., transfer high voltage to the anode-grid gap) for 50 μsec or more. The magnetic field level has by this time fallen considerably, and the tube may restrike. It has been observed in some pulses that the grid voltage rises to epy upon interruption, but begins to fall toward ground after a pause of 1 to 2 μsec, while the anode remains at epy. An implication is that this short time period is sufficient to deionize the anode-grid gap, but that grid-to-cathode capacitance in the tightly coupled tube-magnet system

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prevents the grid from dropping to ground potential. This requires that the interaction section deionize before the anode-grid region, preventing a discharge of the capacitive voltage through the discharge channel. An explanation of this nature would concur with observations of the variable frequency of occurrence of long to short time period duration of high grid potential, since occurrence of the two effects would depend upon which of the two regions deionized first. Difficult to explain, however, is the lack of decay of egk after even 50 μsec. Furthermore, introduction of additional capacitance between grid and cathode increases the rate of fall of grid potential, while the opposite would be expected for RC decay. Use of resistance between grid and cathode was also tested without changing the egk behavior or reducing restriking.

Further circuitry must be tested to bring the grid potential to ground 20 to 30 μsec after interruption without causing grid voltage oscillations, and which can tolerate the rapid $\frac{dV}{dt}$ during interruption. Use of the RSI in a free-running mode must also be considered more carefully, since such operation eliminates all triggering requirements, and, in particular, the need to isolate the grid trigger circuit for the full Ebb voltage.

2.3 RSI 7-2

2.3.1 Fault Interruption - Data Summary

Figure 8 details the results of interruption tests for the RSI 7-2. Bq levels are plotted versus ib and Ebb. Reference curves to the RSI 003 are included. Point B for the RSI 003 represents a discharge channel of length, L = 11.5 inches. The length of the center of the RSI 7-2 interaction channel = 12 inches.

Empirical results for average Bq requirements for the two tubes are:

RSI 003 (normalized to Ebb = 15 kV, ib = 300 amp)

$$Bq = 0.97 \ L^{-0.78} \ Ebb^{1.25} \ ib^{0.24} \qquad P = 0.3 \ torr$$

RSI 7-2 (normalized to Ebb = 9 kV, ib = 200 amp)

$$Bq = 0.79 \ (L = 36 \ cm)^{-0.78} \ Ebb^{1.5} \ ib^{0.27} \qquad P = 0.3 \ torr$$
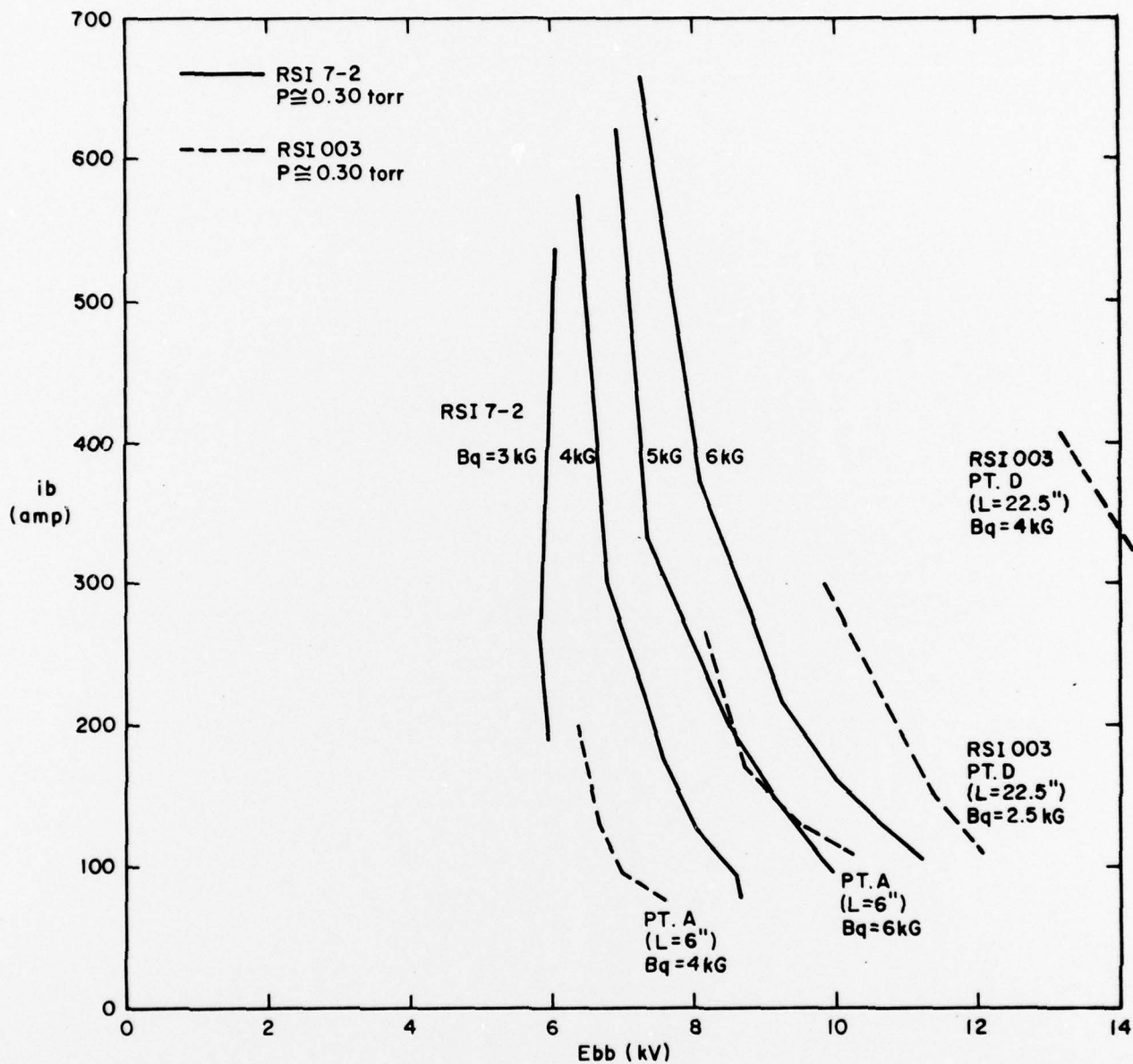
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Figure 8. Interrupting Magnetic Field versus Tube Voltage
and Current for RSI 7-2.

Scatter for RSI 7-2 data is given in Tables 1 and 2. The higher value of β (Bq α L^{-m} Ebb β ib δ) for the RSI 7-2 results in decreased efficiency of interruption at higher Ebb, causing a shift to the right of the Bq curves shown in Figure 8. The cause for this behavior is not clear; a related observation is that wall damage to the RSI 7-2 occurred largely at the points of protrusion of the inside bends into the plasma discharge (Figure 9).

During interruption, the plasma column apparently does not follow the curvature of the wall, but shortens its path as shown in Figure 9. These conclusions are drawn from the location of wall damage to the glass channel. Heaviest plasma tracking is observed at points A, C, E, G, and I, and these points display a wider plasma channel tracking. Point A displays the heaviest damage and some narrow branched tracking which could be caused by local arcing. Point B does not present obvious evidence of arc damage, but rather a somewhat wider (0.5 mm) and more uniform track mark. The turn-edged damage of differing width is probably due to a constricted discharge pressed against the interaction wall to a greater degree at points A, C, E, G, and I than at B, D, F, and H, flattening it and causing increased wall heating at the former points. The hotter central portion of the discharge presumably serves to "clean" the wall at that point, causing a two-sided outline.

2.4 THIN CHANNEL QUENCHING

The RSI 7-3 tube (Figure 10) was built to test possible fault interruption by grid-quenching. This tube utilized a long grid with a restrictive grid aperture of 0.084 inch diameter. Thyratron grid-quenching phenomena are observed at grid current densities of 10,000 amps/sq. in. This corresponds to an expected 55 amp quenching level for an aperture of the size used.

The RSI 7-3 did not undergo quenching at any normal operating condition. Quenching was observed only at very low Ef, presumably due to cathode current limitation. In addition, the tube proved difficult to trigger, had a high grid voltage drop, and operated in a variety of modes, including the normal glow discharge, an arc discharge from the tip of the grid structure, and both arc and glow discharges from the base envelope seal of the grid structure.

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Table 1. Experimental Values of β for $Bq\alpha(Ebb)^{\beta}$ for the RSI 7-2 (P = 0.3 torr).

ib (amp)	100	125	175	225	275
β	1.46	1.45	1.26	1.72	1.65

Table 2. Experimental Values of δ for $Bq\alpha(ib)^{\delta}$ for the RSI 7-2 (P = 0.3 torr).

Ebb (kV)	7	7.5	8	8.5	9	9.5	10	10.5	11
δ	0.21	0.29	0.29	0.30	0.29	0.32	0.37	0.29	0.41

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Figure 9. RSI 7-2 Damage Survey.

ANODE

GRID APERTURE 0.084"

0.025" ⊥

GRID

0.130"

ONE INCH

DEMOUNTABLE
CATHODE
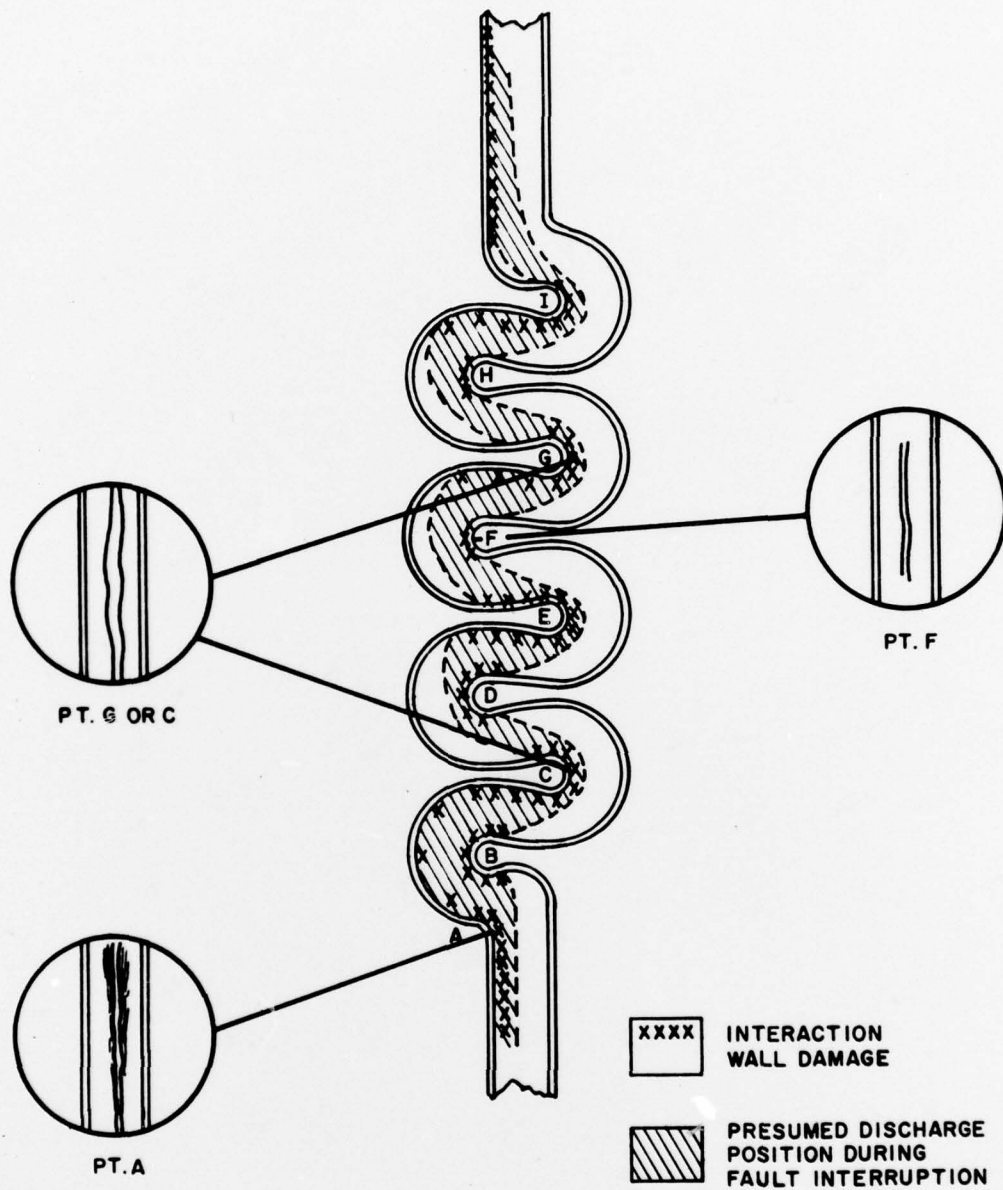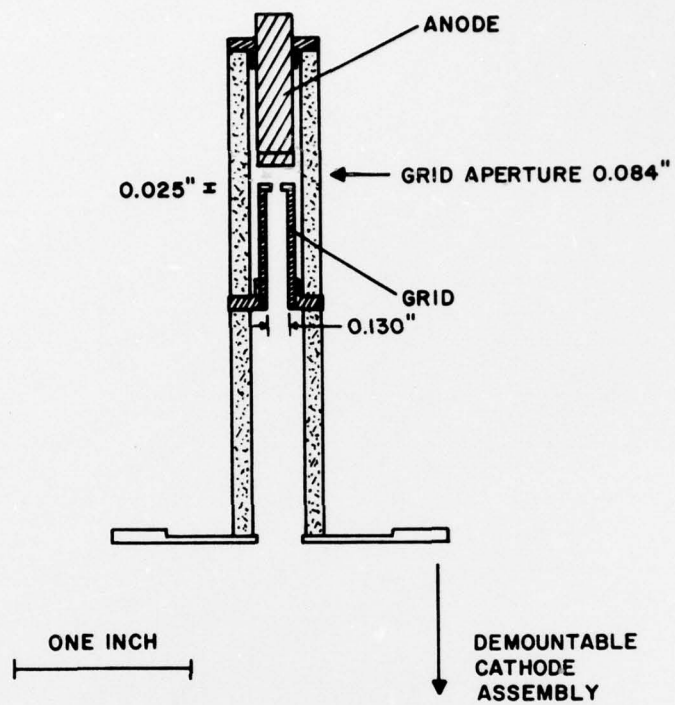ASSEMBLY

Figure 10.   RSI 7-3.

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A strong (8 KG) magnetic field was applied across the anode-grid gap as a test for fault interruption. The application of a transverse field across a triple grid holdoff structure has been used by Wheldon (Reference 1) as an opening switch. The utilization of a thin channel anode-grid design tests an opening switch application where the total switching magnetic field energy has been minimized by volume reduction.

This test was not successful. The application of a field as high as 10 kilogauss provided fault interruption at only very low voltages (Ebb = 2 kV). It appears that a redesign would be necessary to add additional grids, as Wheldon did. These cannot readily be stacked adjacent to one another in a thin channel tube in a reentrant design, but require instead a design providing either (1) feed-through through the insulator wall (which could result in a tendency to arc from the metal-dielectric junction), or (2) stacking of a complete RSI 7-3 type anode grid assembly, which would result in a long, thin central channel and a correspondingly high tube voltage drop.

2.5 OTHER TUBE DESIGNS AND MODIFICATIONS TO THE EXPERIMENT

The RSI 006 six-section 0.25-inch I.D. uniform channel maze tube suffered ceramic channel separation during brazing which could not be repaired despite successive rebraze and fill operations. The decision was made to await RSI 10 results before constructing an alternate high voltage/high current interruption scaling tube.

MACOR ceramic seals continued to prove obstinate, with multiple seal fractures continuing to occur despite some success. Consideration of this problem was temporarily delayed to concentrate on RSI 10 construction.

Major experimental changes were made. The Machlett ML-7845 75 kV power triode was installed and tested at a low repetition rate, up to 15 kV without difficulty. The grid bias circuitry, driver isolation transformer, and low repetition rate driver performed successfully. Series operation of the triode with the RSI 7-2 (anode-grid shorted) was successful, although fracture of the RSI tube prevented further testing of auxiliary circuitry to allow operation without an RSI anode-grid short circuit.

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The experimental test bench was moved to a new location, providing darkening capability for improved visual observation of tube discharge character, while retaining accessibility to modulator power.

3. CONTINUING WORK

3.1 DISCHARGE COLUMN DIAMETER STUDY

Results to date are inconclusive regarding the effect that the I.D. of the discharge tube has upon fault interruption. To clarify this particular, two tubes with a total of four discharge channels of differing diameters are being constructed. Pyrex channels are being used to provide ease of construction with moderate discharge erosion resistance.

3.2 INVERSE PINCH TUBE

An inverse pinch tube, as described in the 1976 proposal, is being constructed. Two coaxial glass tubes are connected such that the inner channel penetrates the outer wall in a vacuum tight seal at each end of a six-inch length. A coaxial magnet coil is built about the tube, where the magnet current is carried inside the central glass channel, with a return path outside the outer channel. A circular magnetic field is thereby devised in the annular portion of the tube, through which the discharge is compelled to travel. The resultant plasma $\vec{I} \times \vec{B}$ force drives the discharge against the inner or outer channel wall.

This geometry studies the possibility of using strong magnetic fields near the central conductor to provide easier fault interruption. The coaxial geometry constrains the magnetic field principally to the plasma discharge volume, reducing fringe field losses to those of the conductor leads to the magnet capacitor and its resistive load. Disadvantages are the requirement for high magnet current levels, and the radial nonuniformity of the magnetic field (which may or may not effect current interruption).

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3.3 FLAT WALL DISCHARGE TUBE

Circular cross-section discharge columns invariably center the fault discharge in a restricted channel along the tube length. The use of a flat wall against which the discharge is driven provides a lower plasma current density at the wall surface and reduces the wall surface temperature (potentially reducing secondary electron emission and wall material vaporization). Since Bq has been seen to be a function of $ib^{0.25}$, and since theory suggests that the discharge diameter is independent of the discharge current, the implication is that Bq is a similar function of the plasma current density, j, at the wall surface. A glass channel having a 1/4-inch wide flat internal wall surface is being constructed. An increase of the discharge width from an observed 1/16 inch to 1/4 inch reduces j by a factor of four, and could reduce Bq by:

$$Bq \; flat = (1/4)^{0.25} \; Bq \; circ = 0.71 \; Bq \; circ$$

3.4 LOW PRESSURE RSI 11 SERIES

In conjunction with the RSI 10 DD 30 kV design, two tubes are under construction to test 30 kV holdoff capability of a single cavity HY-6 based anode-grid structure. Anode-grid spacing has been increased, and grid baffling has been decreased to allow operation at low pressure.

4. DISCUSSION OF RESULTS AND CONCLUSIONS

Low pressure tube operation continues to present itself as the most hopeful design alternative for an interruptible thyratron. Interaction channel pulse voltage drop, interrupting magnetic field equipment, and re-strike probability all decrease with decreasing tube pressure. The difficulty lies in the design of a high voltage structure which will provide sufficient high voltage holdoff while allowing reasonable tube triggering requirements, anode-grid voltage drop, and low tube jitter and delay. Investigation must be made into the character of loosely baffled, and possibly unbaffled, thick-grid holdoff structures.

It is believed that restriking is not an innate characteristic of RSI tubes, and can be eliminated with further attention to the external circuitry and trigger system and possibly to greater isolation of the high voltage holdoff structure. The observed reduction of restrike incidence described in this report supports this belief. There is no physical reason that restrike cannot be eliminated, so long as the grid is treated properly.

Grid-quenching does not appear to offer the possibility of providing reliable high voltage interruption in conjunction with normal pulse low voltage drop and jitter. The possibility remains that thin dielectric channels may provide the same quenching mechanism without resulting in pulse noise and arcing.

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